Summary of Run II Accelerator Physics Issues

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Director's Review of Run II Luminosity Plan

October 17-18, 2002

Accelerator Physics Issues for Run IIa

- Interesting AP issues, many of which have been presented earlier:
  - Tevatron: beam-beam, halo development and collimation, orbits & apertures, instabilities, lattice, etc.
  - Main Injector: emittance growth, injection match, coalescing, transition crossing, etc.
  - Antiproton Source: beam-gas, IBS, lattice, chromaticities, damping systems, etc.
  - Proton Source: space charge, injection, energy deposition, instabilities, etc.
  - Recycler: …

Major Issues

Luminosity given by:

$$L = \frac{3 f_0 B N_p N_{\bar{p}} \gamma}{\beta^* \sqrt{(\varepsilon_x^p + \varepsilon_x^{\bar{p}})(\varepsilon_y^p + \varepsilon_y^{\bar{p}})}} \sqrt{\pi} \left(\frac{\beta^*}{\sigma_z} \right) e^{(\beta^*/\sigma_z)^2} [1 - \Phi(\beta^*/\sigma_z)]$$

or,

$$L = \frac{2 f_0 \gamma}{\beta^* r_0} \frac{\xi_0 B N_{\bar{p}}}{(1 + \varepsilon^{\bar{p}}/\varepsilon^p)} \cdot H(\beta^*/\sigma_z)$$

ξ_0 = beam-beam parameter ~ 0.01;
r_0 = classical radius; H = hour-glass

Presesntly, $$L = \frac{2(48 \cdot 10^3)(10^3)}{(35)(1.5 \cdot 10^{-16})\text{cm}^2 \sec} \frac{(0.5 \cdot 10^{-2})(80 \cdot 10^{10})}{1 + 1/2} \frac{3}{5}$$

= 3 x 10^{31} cm^{-2} sec^{-1}

Major Issues: beam-beam interaction, emittance preservation (transverse & longitudinal) → transfers, beam instabilities, lifetime, detector background

Physics Support for Run IIa

Support provided by Beam Physics Department:

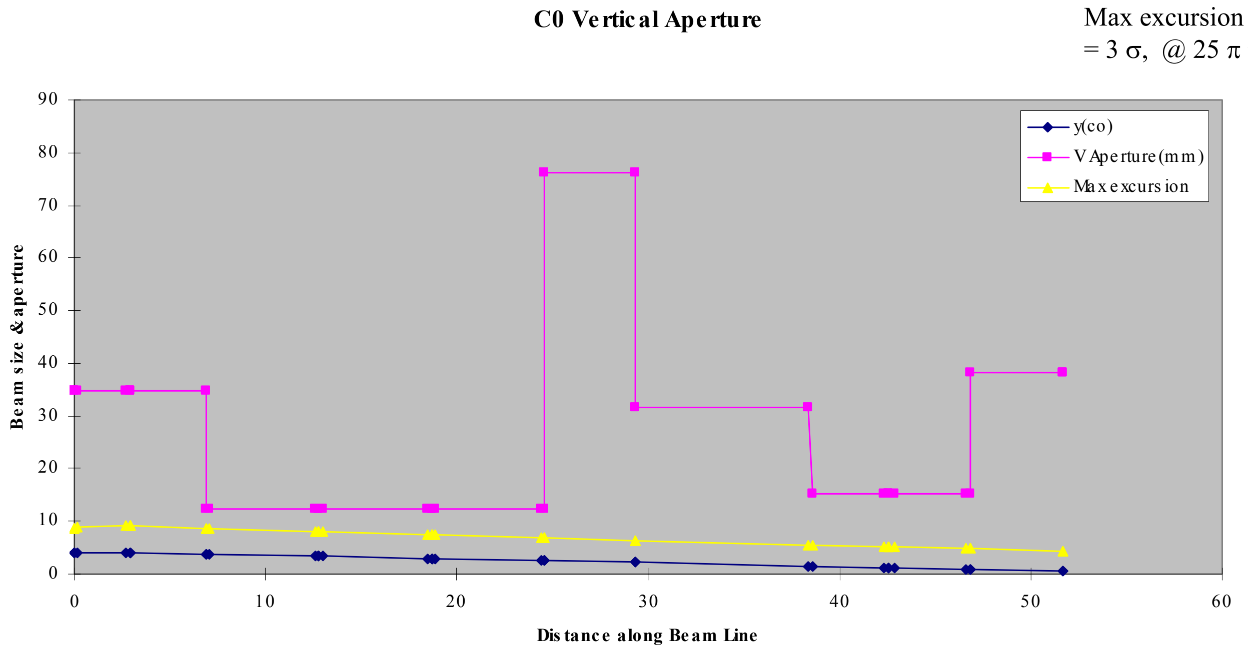
- **Injectors, Recycler –**
  - **Coalescing calculations, instabilities, beam transfers, longitudinal dynamics, Booster injection magnet, etc.**

This talk will concentrate on :

- **Tevatron --**
  - **Lattice efforts -- helical orbits, aperture, …**
  - **Beam-beam effects – tunes, dynamic aperture**
  - **Longitudinal instabilities**
  - **Energy deposition / backgrounds**

C0 Aperture

Max excursion
= 3 σ, @ 25 π mm-mr



- Unnecessary "abort" Lambertsons generate small vertical aperture
  - helix adjusted (4 sep.'s rather than 2) from its design to produce small vertical separation at this location at injection
  - Lambertson nonlinearities studied; not an issue for operation (B. Erdelyi)

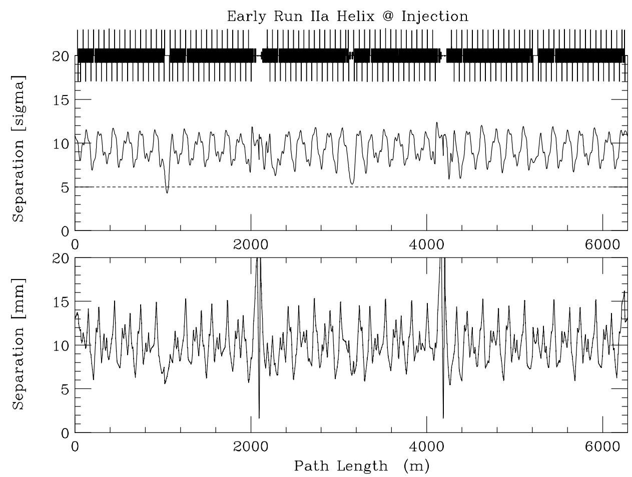
C0 Aperture (cont'd)

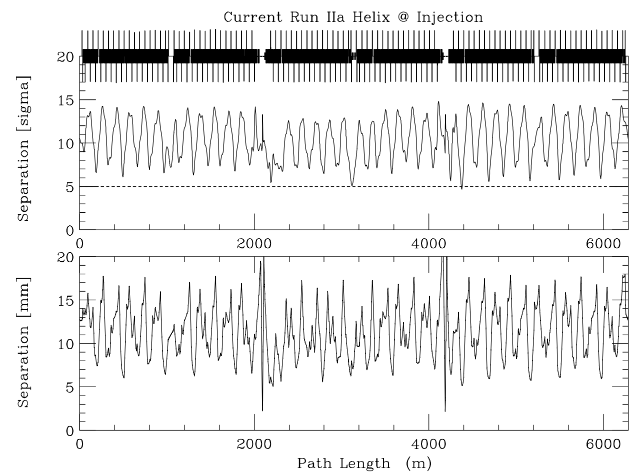
- **Options:**
  - **Replace Lambertsons with warm MI dipole magnets**
  - **Reconfigure straight section with cryo magnets (as in other Tev straight sections)**
    - **Option for moving – but maintaining – synch-light monitor has been proposed (J. Johnstone)**
  - **Effects of nonlinearities of MI magnets have been analyzed (T. Sen) and are small**
  - **Gain from increased aperture…**
    - **allows for either**
      - **More room for larger emittance beams**
      - **Room to increase p-pbar separation**
      - **…both**

C0 Aperture (cont'd)

- **If C0 vertical aperture restriction is removed, then can go back to the original design helix, giving smaller variations of beam separation around the ring**
- **Can also consider other helix schemes for injection**
  - **Consider using more than 2 separators during injection with the increased aperture; area of present studies**
- **Next aperture issue – A0 …**

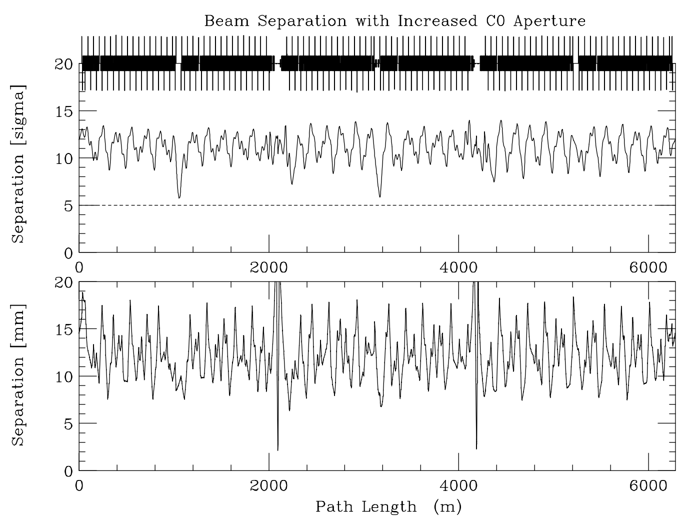
C0 Aperture (cont'd) -- J. Johnstone





Current helix moves C0 separation to horizontal plane

Plots start at F0

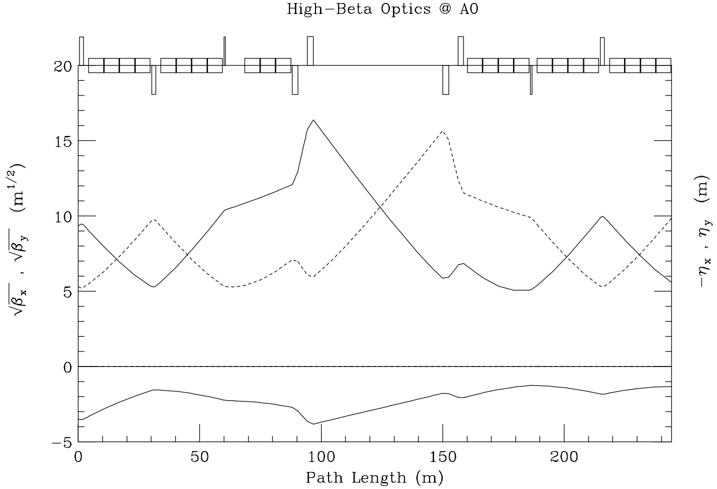


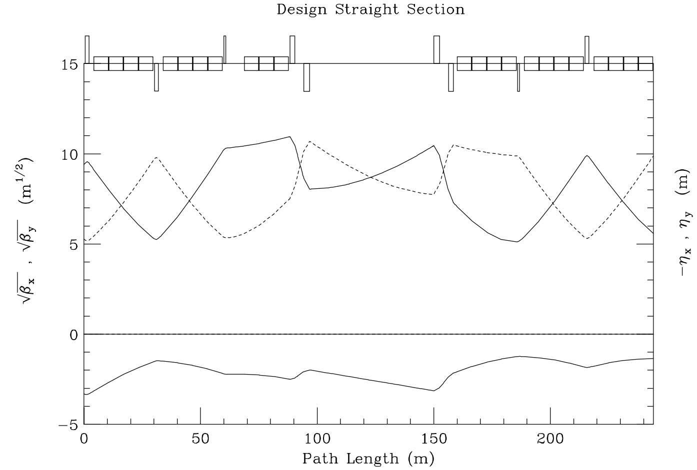
Removing C0 restriction allows for larger overall separation

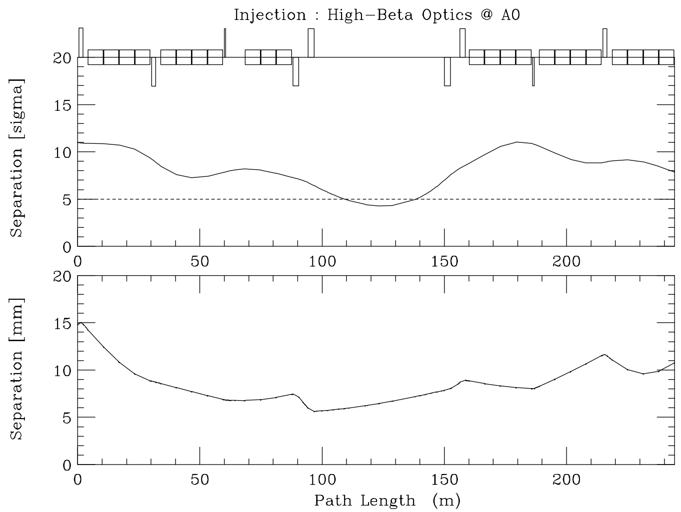
A0 Aperture

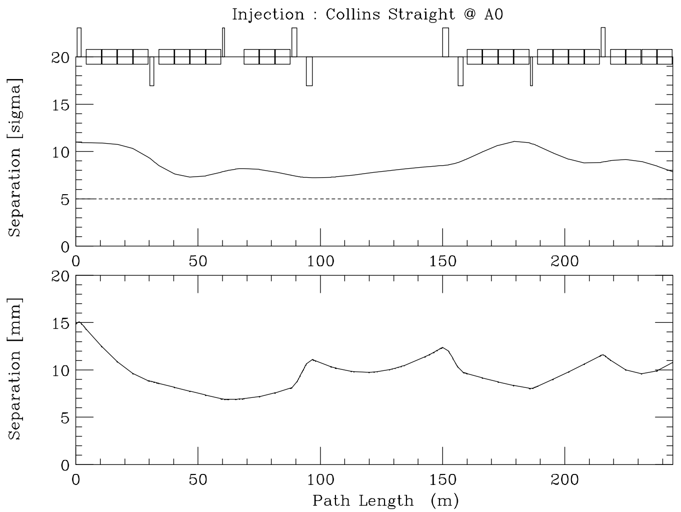
- With C0 vertical aperture restriction removed, and original design helix restored, the closest approach of the two beams (in units of beam size) occurs in A0 region – "high beta" optics used for slow resonant extraction
- Thus, consider changing A0 optics to the original "standard" Collins straight section
- Work on-going to investigate C0 and A0 options; decisions tied to timing of long shutdown and scheduling/manpower issues for implementation in the tunnel

A0 Optics and Helical Orbit





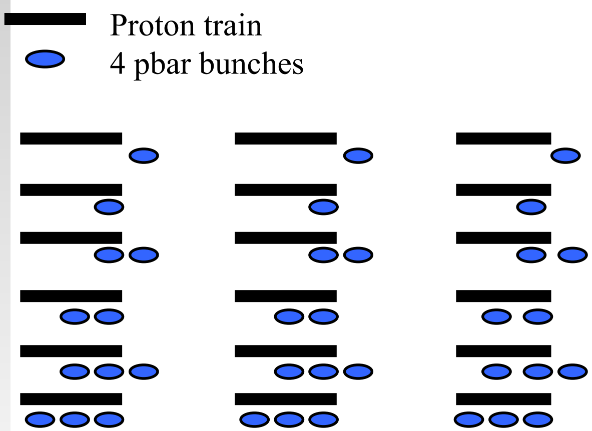


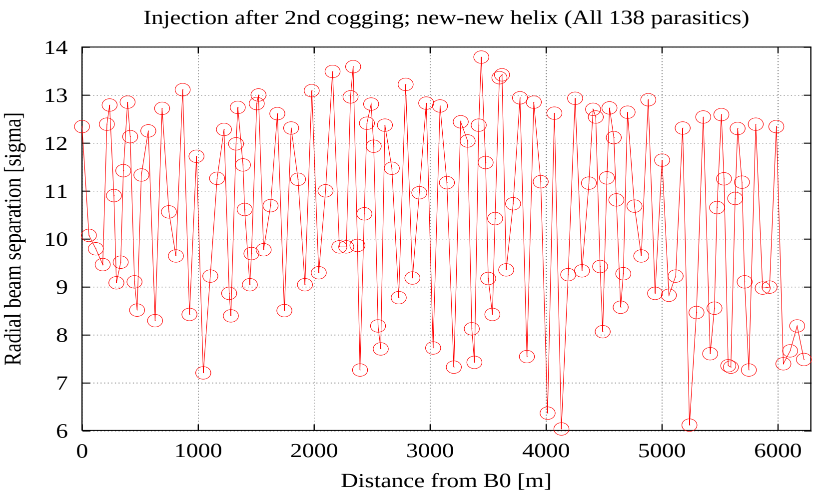


Courtesy
J. Johnstone

Beam-beam Simulations and Experiments

- **Main issues are at injection – separated orbits (helix) with 72 long range interactions**
- **Look at:**
  - **Particle tracking calculations of dynamic aperture**
  - **Dynamic aperture vs. tune**
  - **Comparisons of calculations with observations & experiments**

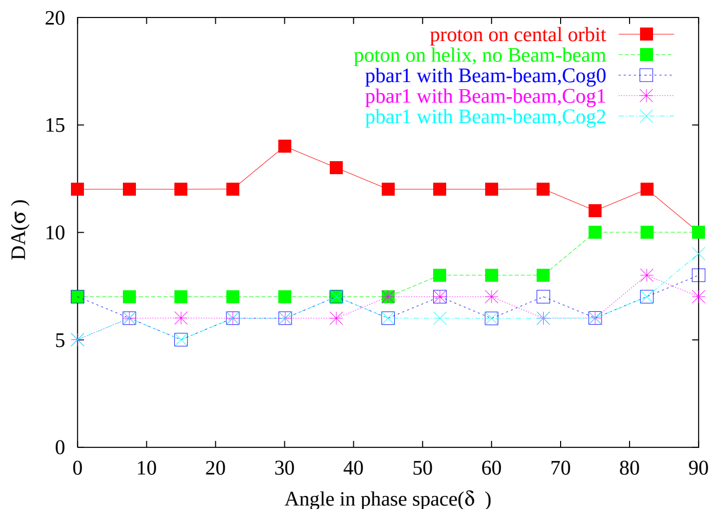




Injection Dynamic Aperture Calculations (M. Xiao)

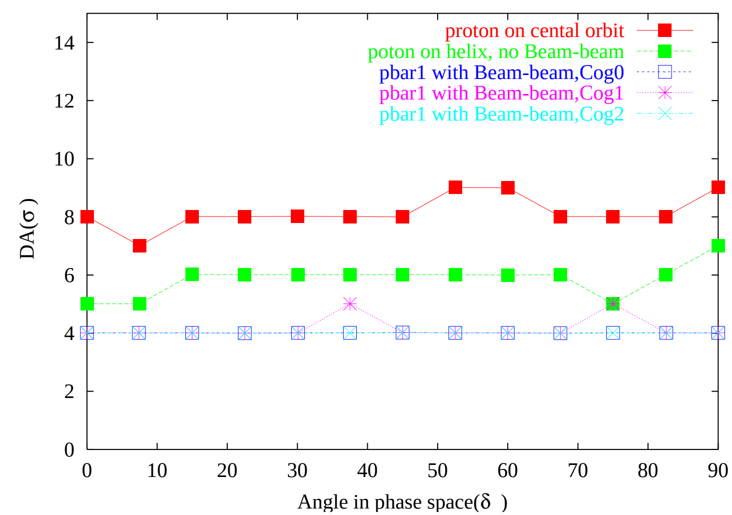
Pre/Early-Run studies

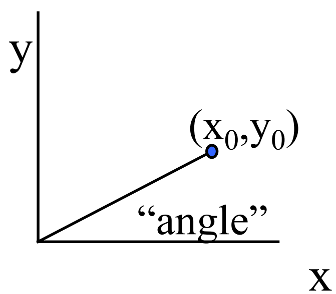
15π emittance, dp/p=0.4e-4 (1σ),
$\nu_{x,y}$=(0.585,0.575), Original helix



Present Conditions

25π emittance, dp/p=13e-4 (3σ),
$\nu_{x,y}$=(0.583,0.575), “new-new” helix



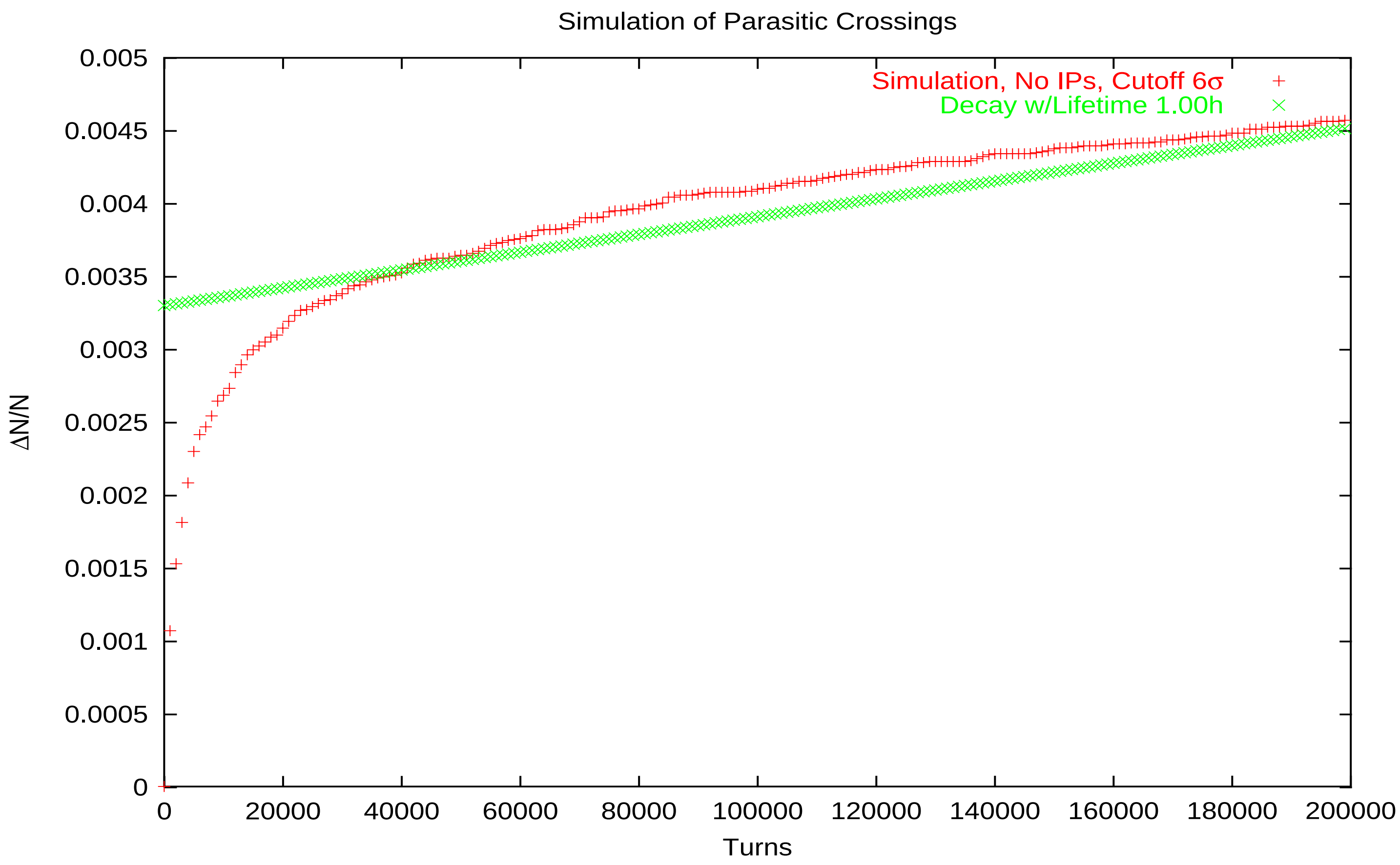


Starting at B0, center of beam - beam kick; 10^5 turns

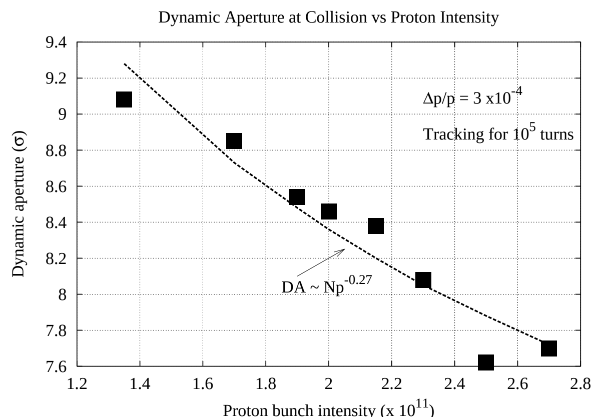
Behavior on/off helix consistent with DA calculations

Multi-particle modeling (Kabel, Cai; SLAC)

- 10^6 particles, long-range interactions at 150 GeV, helical orbit…



980 GeV Dynamic Aperture (T. Sen, M. Xiao)

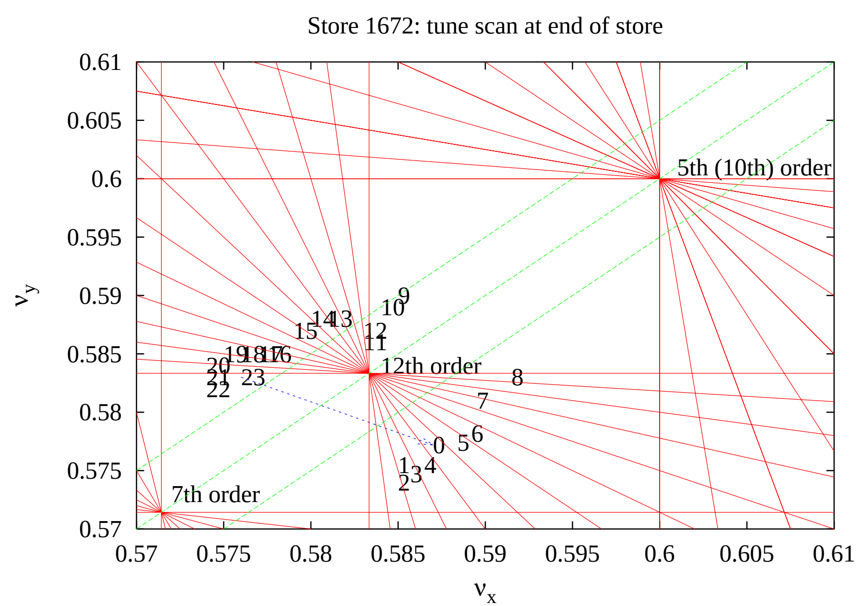


Have calculated effects due to proton bunch intensity, tunes, beam separation, …

Tracking results:

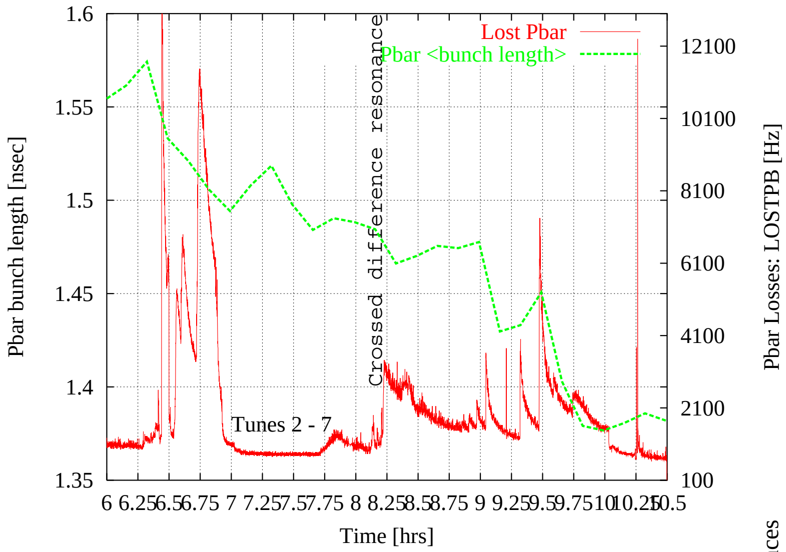
	Bare tunes	4D DA ($(\langle DA\rangle, DA_{min})$)	6D DA ($\delta_p = 3 \times 10^{-4}$) ($(\langle DA\rangle, DA_{min})$)
A0	0.585, 0.575	(10.0, 9.0)	(7.8, 6.0)
A1	0.575, 0.569	(9.2, 7.0)	(5.1, 4.0)
A2	0.577, 0.571	(9.3, 8.0)	(7.5, 6.0)
A3	0.579, 0.573	(9.4, 9.0)	(8.1, 7.0)
A4	0.583, 0.577	(9.8, 9.0)	(7.6, 6.0)
A5	0.585, 0.579	(9.6, 8.0)	(7.5, 7.0)
A6	0.587, 0.581	(9.5, 8.0)	(7.5, 6.0)
A7	0.575, 0.585	(11.0, 9.0)	(8.6, 7.0)
A8	0.577, 0.587	(10.7, 9.0)	(8.4, 8.0)
A9	0.579, 0.589	(10.5, 9.0)	(7.6, 5.0)
A10	0.581, 0.591	(10.0, 8.0)	(7.0, 5.0)
A11	0.583, 0.593	(9.5, 6.0)	(4.8, 3.0)
A12	0.585, 0.595	(8.5, 6.0)	(1.9, 1.0)
A13	0.551, 0.561	(10.9, 9.0)	(7.2, 5.0)
A14	0.553, 0.562	(10.7, 9.0)	(6.2, 5.0)
A15	0.555, 0.564	(10.2, 9.0)	(7.2, 6.0)
A16	0.556, 0.566	(9.9, 8.0)	(5.7, 3.0)
A17	0.558, 0.568	(11.0, 9.0)	(5.4, 3.0)
A18	0.560, 0.570	(10.5, 8.0)	(5.4, 3.0)

Table 7: Dynamic aperture, both 4D and 6D, calculated after 10^5 turns at different tunes shown in Figure 18. All beam-beam interactions were included. A0 is the nominal tune, A1, A2, A17 and A18 are close to 7th order resonances while A12 is close to 5th order resonances. We observe that at tunes away from these low order resonances the dynamic aperture does not change significantly.

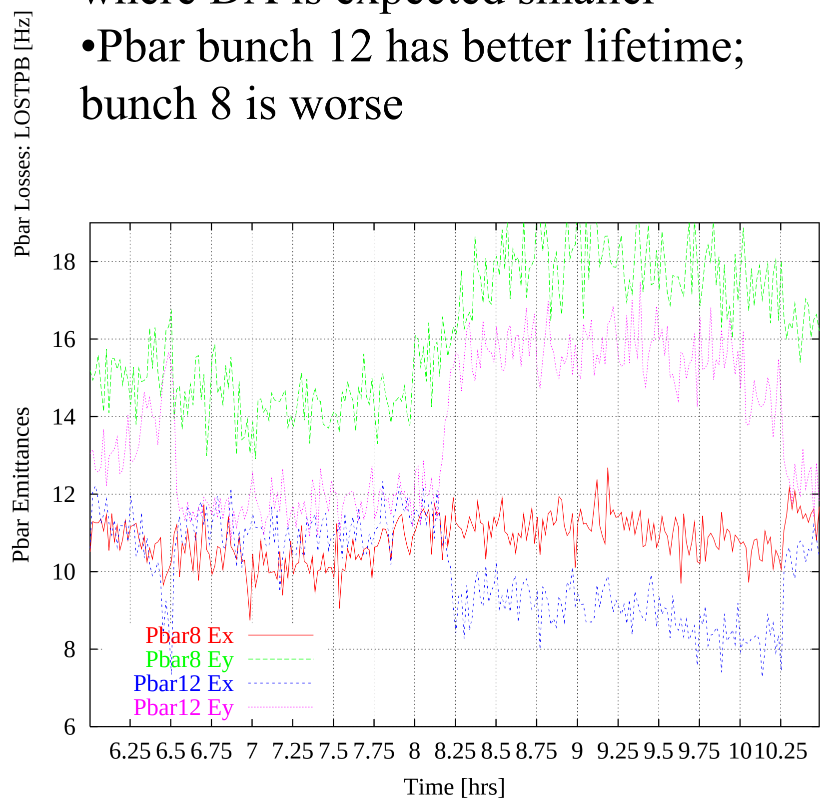


980 GeV Dynamic Aperture (T. Sen, M. Xiao)

Compare with experimental results…



- Losses, lifetimes impacted at tunes where DA is expected smaller
- Pbar bunch 12 has better lifetime; bunch 8 is worse



Emittance exchange observed as crossing coupling resonance (pbars); not seen for protons

Lattice investigations …

- **Transverse coupling correction is higher than during previous run (N. Gelfand, et al.)**
  - **If main skew quad circuit turned off, $\Delta\nu_{min}$ ~ 0.4**
  - **Models, using operational currents, do not agree with observation (x10!) – unknown source(s) of coupling**
  - **Vertical dipole correctors in E-F-A sectors have large average offsets**
    - **Around ring, $<\theta_y>$ = 16 μrad; $<\theta_x>$ = 0.7 μrad**
    - **Through portions of E-F-A, $<\theta_{y>}$ = 80 μrad seen**
  - **Alignment measurements in above regions show rolls of 2-8 mrad (worse in dipoles); appears to change over time; need for total survey & alignment of Tevatron**

Lattice investigations …

- Transverse Coupling in IR's (B. Erdelyi, et al.)
  - Was issue in Run I
    - rolled triplet quads (~10 mrad!)
  - Studies performed on B0 (CDF) region over three study periods; still to do: D0 region
  - Assume design model in region for computing transfer matrices, but rolled triplet magnets allowed; influence of detector magnets neglected
  - H&V BPM measurements made of responses to local orbit distortions through region; 64 orbit measurement produced 64x4=256 equations in 3 variables (for each triplet)
  - IR's have local skew quads; measurements made with these magnets both on and off.

Lattice investigations …

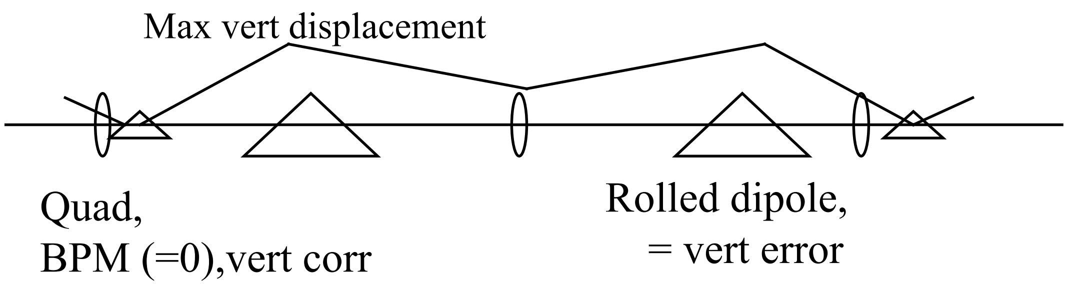
- **Transverse Coupling in IR's -- results for B0 (CDF)**
  - Roll angles obtained (nonlinear fitting procedure):

Quadrupole	All data	Skew quads off	Recent Meas.
Q2F	0.00	0.00	0.34
Q3D	1.55	-1.59	-0.07
Q4F	-0.04	-0.04	no data
Q4D	1.38	1.55	no data
Q3F	0.07	-0.05	-0.04
Q2D	0.02	0.10	0.21

Promising method; T-B-T BPM system would greatly increase resolution of the method

Will continue for D0, perhaps other regions of the Tevataron

Lattice investigations …



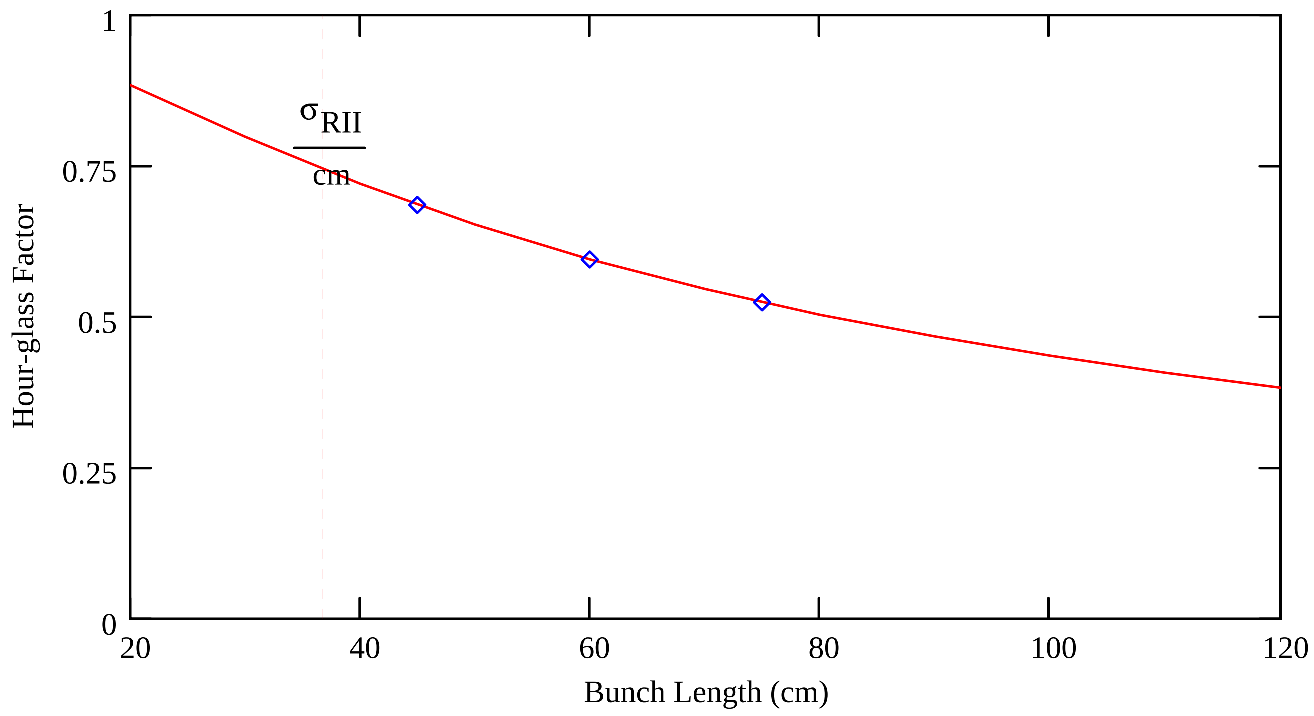
- **Systematic offset in magnets due to rolls and corrections:**
  - **Rolled quads – linear coupling**
  - **Rolled dipoles, corrected by vertical steering magnets –**
    - **"scalloped" orbit through the dipole magnets**
    - **Generates ~1-2 mm vertical offsets through dipoles**
      - **Therefore, more coupling due to b_2 feed-down**
      - **Other nonlinear effects?**
    - **Being investigated further…**

Longitudinal Issues

- Bunch length growth at 150 GeV
- Losses during the Ramp
- Beam instabilities – dancing bunches
- DC beam generation during store

- Effects –
  - Hour-glass effect: $\beta(s) = \beta^* + s^2/\beta^*$
    - since $\sigma_z > \beta^*$ -- > makes a hit on luminosity
  - Dispersion mismatches → transverse emittance growth during transfers (observed effect)
  - Vertical dispersion in Tevatron – effecting luminosity? (probably not; should be small effect)

Hour-glass effect

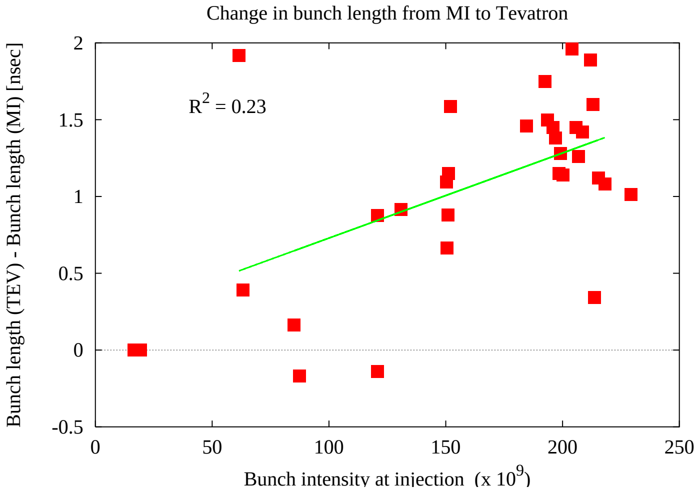


Presently operate around 60 cm (~2 nsec)

Losses through the Ramp (T. Sen, F. Schmidt, et al.)

- **Study performed with 36 proton (only) bunches, with different characteristics**
- **Varied -- momentum spread (coalescing), emittances (scraping), intensities (Booster turns)**
- **Measured over time: intensities, emittances, ramp efficiencies, lifetimes at 150 GeV, etc.**
- **Strong correlation of ramp efficiency with bunch length --> longitudinal scraping**

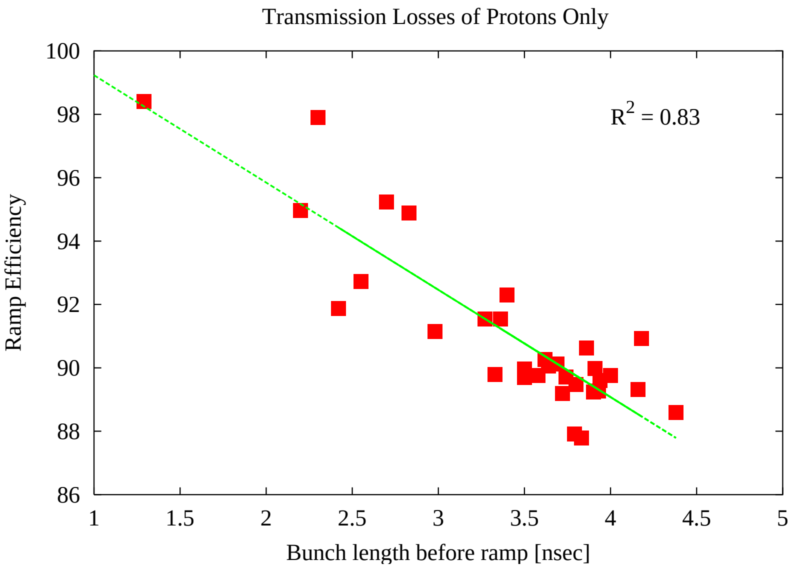
Losses through the Ramp (T. Sen, F. Schmidt)



Main Injector bunch length at 150 GeV is ~2.5 nsec; increases by ~1-2 nsec upon injection into Tevatron

- Ramping efficiency worse for longer bunch lengths

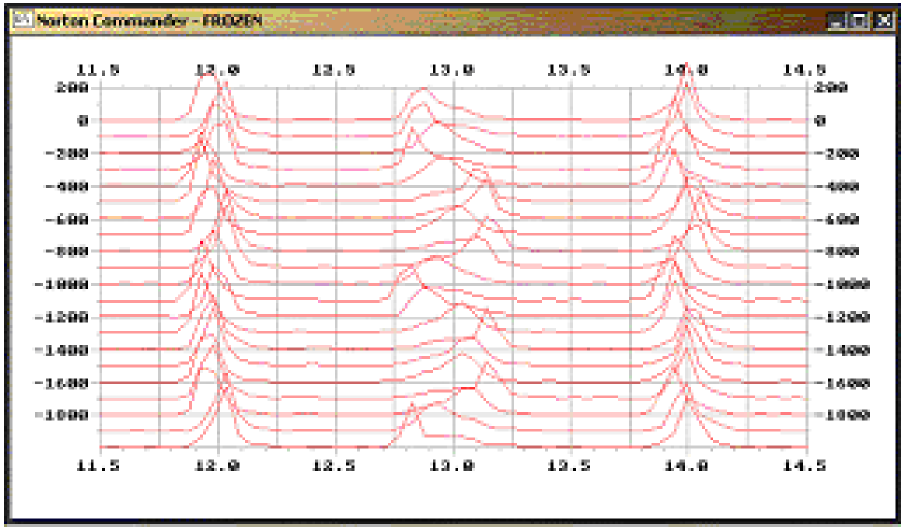
- If could be preserved, would give 1.5 nsec (rms) bunches at 980 GeV, rather than 2.2 nsec → +16% gain in luminosity (hour glass)



Instabilities -- Dancing Bunches

- **Long-term coherent synchrotron oscillations of proton bunches observed in Tevatron, no damping of oscillations, no increase in emittance**
- **Dampers are "cure" for now; will return?? Would still like to understand source…**

Mountain range plot of uncoalesced bunches dancing in the Tevatron, July 2002; here, 3 from a train of ~30; courtesy R. Moore.



Dancing bunches

- Charge distribution different for coalesced / uncoalesced bunches; bunches oscillate at differing frequencies
- So far, uncoalesced data studied in detail
- Purely imaginary inductive impedance due to space charge -- a modified Keil-Schnell criterion (Balbekov, Ivanov, 1991) -- yields $|Z/n|_{thresh}$ that can sustain such an oscillation
- For Tevatron, at 10^{10}/bunch, ~ 1 Ohm (numerically in right ball park)
- Computer model…

Dancing bunches (V. Balbekov)

- **Compute longitudinal density $\rho(\phi)$, assuming**

$$\rho(\phi) = \frac{3\pi e N}{2\lambda\phi_0}\left(1 - \frac{(\phi-\phi_c)^2}{\phi_0^2}\right)$$

- **Compute corresponding longitudinal electric field; gives equation of motion of the form:**

$$\frac{d^2\phi}{dt^2} + \sin\phi = -\frac{Q}{\phi_0^3}(\phi-\phi_c) \qquad (t \leftarrow t/T_s)$$

- **For Tevatron, $Q = -6 \times 10^{-13}\, N\, (i\, Z/n$[Ohm]$)$**

Dancing bunches (V. Balbekov)

Linear approximation separates to give…

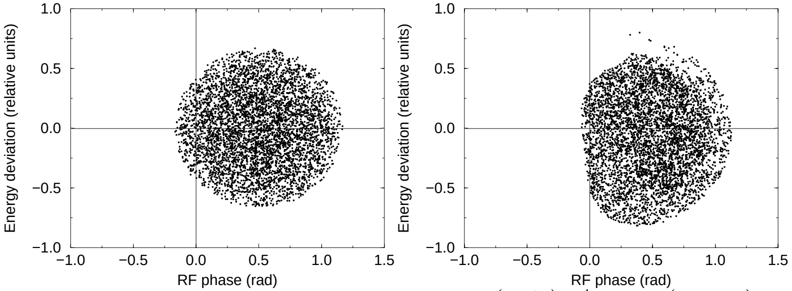
$$\frac{d^2\phi_c}{dt^2} + \phi_c = 0$$

$$\frac{d^2x}{dt^2} + (1 + \frac{Q}{\phi_0^3})x = 0$$

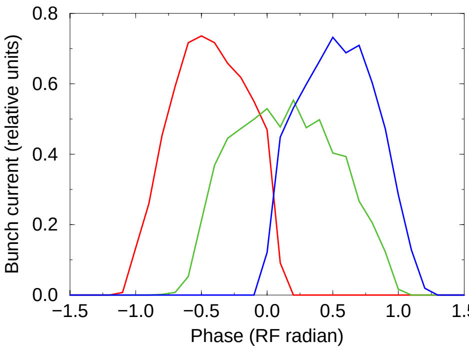
$$(x = \phi - \phi_c)$$

For ϕ_0=const., gives 2 frequencies; mimics observations

Computer simulation:
5000 particles, Q=-0.1, ϕ_0=0.5



Phase space in the beginning (left) / end (right).



Bunch form at interval 1/4 period of oscillations

Work continues…

DC Beam Generation

- Develops immediately at injection, causing losses when ramp – full buckets at transfer
- But, also develops during store
  - Mechanisms unknown; Tevatron Electron Lens (TEL) used as cure
- Collaborative studies with experiments (A. Tollestrup, CDF, for example) -- sensitive measurements of DC beam migrating into abort gaps
  - Indicates protons being lost from buckets at rate of several 10^6/sec or so

DC Beam Generation

- **Phase noise, voltage noise most likely candidates; probably more sensitive to phase noise (motion near unstable fixed points)**
  - **Random turn-to-turn noise:**

$$\frac{dS}{dt} = \frac{3}{2h}\sqrt{\frac{2\pi h|\eta|eV}{E}}eV\,\Delta\phi_{rms}^2$$

***dS/dt* = 1 eV-sec/hour**
→ $\Delta\phi_{rms}$ = 0.4°

    - **Note: would also lead to 2π mm-mr/hour transverse emittance growth due to dispersion in cavities…**

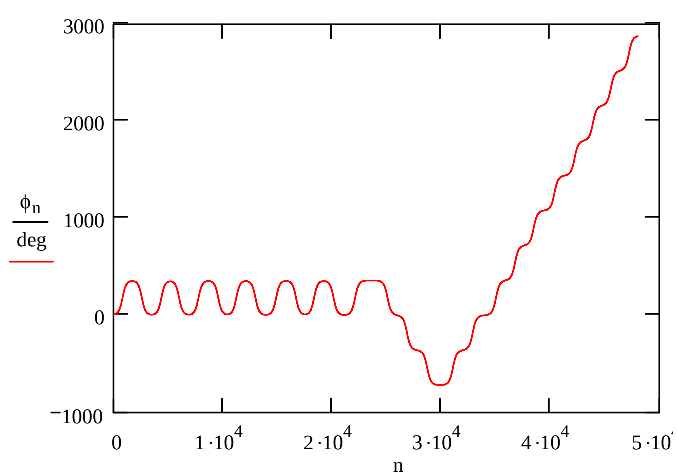
  - **Possibly transverse modulation & synchro-betatron coupling:**
    - **Motion of closed orbit due to varying transverse field gives changing path length ($\Delta C = D\Delta\theta$), and hence varying phase**

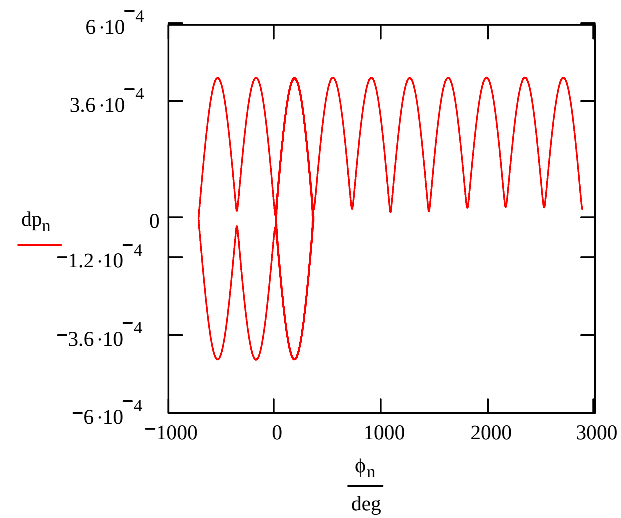
DC Beam Generation

Example: 5 μrad steering error (at *D*=4m) oscillating at 60 Hz (synchrotron frequency is 36 hz) can produce 0.5 degree phase oscillations of bunch center – particles near separatrix will leak out…

$D = 4\,\mathrm{m}$ $\theta_{max} = 5.615 \times 10^{-6}$ $f_m = 60\,\mathrm{Hz}$ $f_s = 35.638\,\mathrm{Hz}$ $g_{max} = 0.752\,\mathrm{deg}$

Initial conditions: $\phi_0 - \pi = -170\,\mathrm{deg}$ $dp_0 = 0$ $\max(\phi - \pi) = 2.697 \times 10^{3}\,\mathrm{deg}$





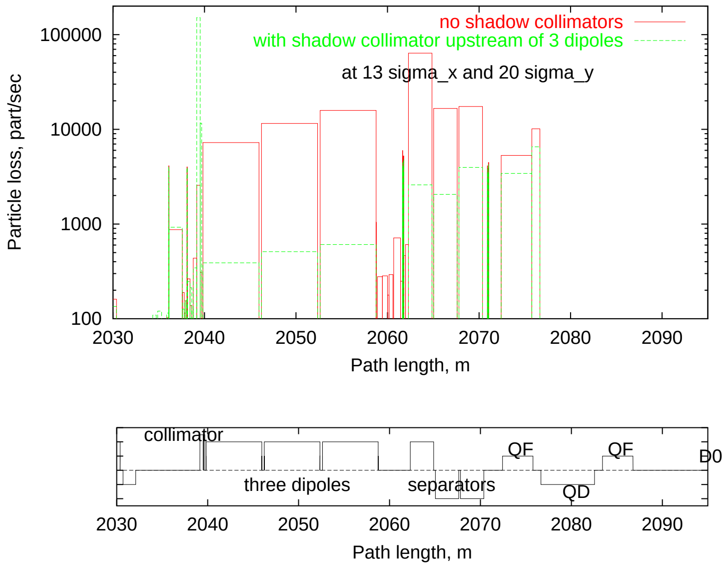
investigation continuing…

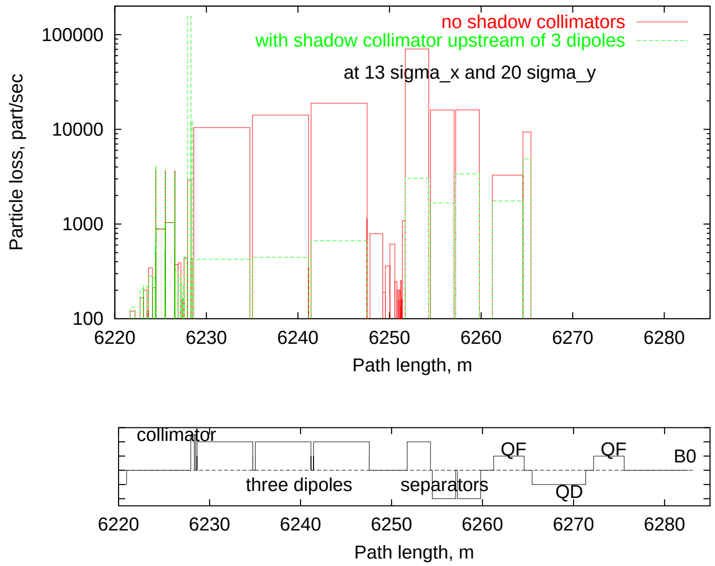
Energy Deposition (Mokhov, Drozhdin, et al.)

- **Loss rates in B0 (especially) and D0 an issue**
- **Present system designed for cure of beam losses due to slow emittance growth – works well as designed; about 0.1% of particles escape system**
- **Large angle elastic scattering off residual gas nuclei and Coulomb scattering, between collimators and IPs, result in higher loss rates at detectors**
- **Detailed MARS model of A-sector, B0 and CDF (including Roman Pots) for beam loss and radiation studies -- suggests use of "shadow collimators"**
  - **0.6 m "mask" just before last dipoles entering IP**
  - **13σ_x and 20σ_y away from beam**
  - **Reduces backgrounds by about 10 times**

Energy Deposition (Drozhdin)

0.6-M MASKS IN BØ and DØ





Collaborative Efforts

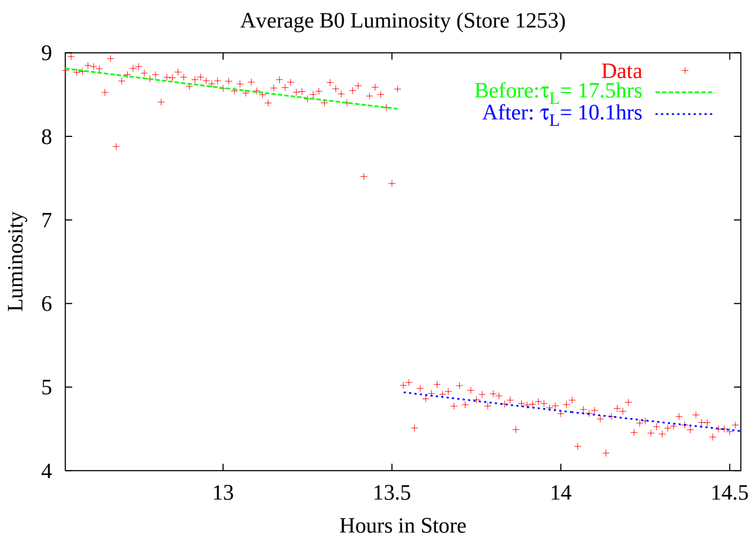
- **SLAC, LBNL -- Long-range beam-beam simulations, using particle-in-cell modeling; SciDAC**
- **UM, LBNL -- Recycler modeling, using MaryLie**
- **CERN, BNL -- physicist exchange; F. Schmidt, W. Fisher, F. Pilat, V. Ptitsyn so far; more to come**
- **ANL, IUCF -- AP groups meeting bi-monthly; so far, sharing computational / experimental experiences on instability issues**

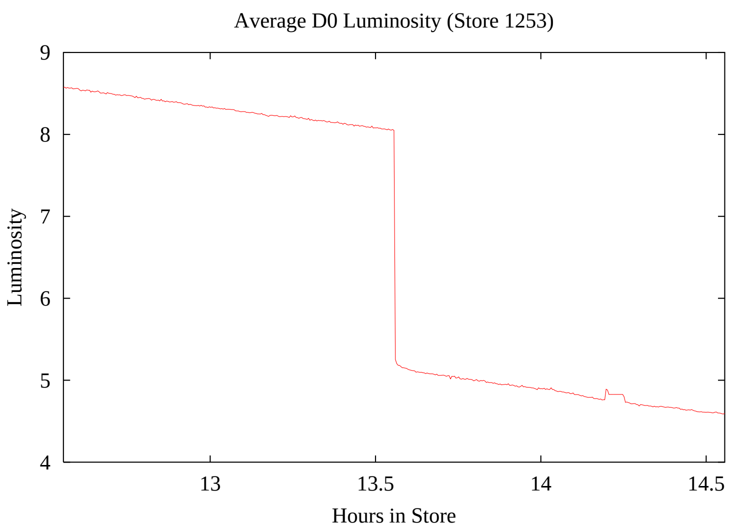
Back-up Material…

Helical orbit separator failure

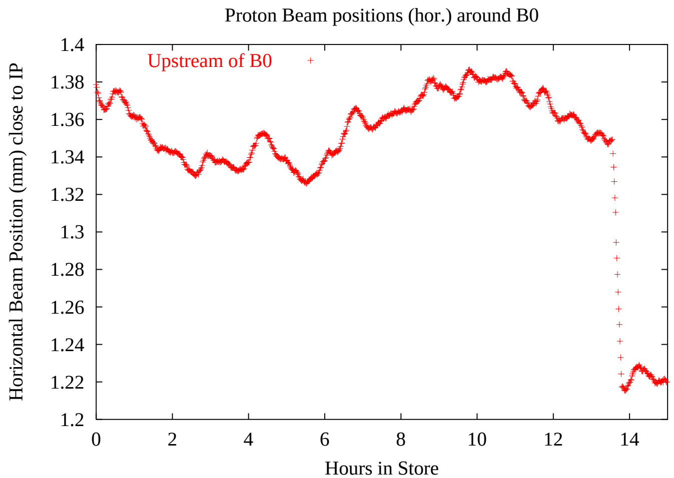
Store 1253: separator (horiz.) at A49 failed:

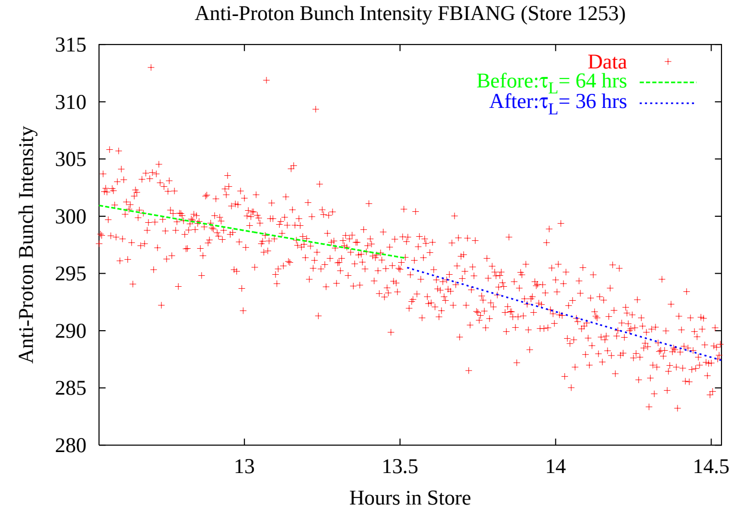
- **Neg. plate went from -90 kV to -25 kV**
- **Field went from ~3.6 MV/m to ~2.3 MV/m**
- **$\Delta\theta$ = +/- 3.4 μrad (opp. sign for p, pbar)**
- **Observed 40% loss in luminosity, beam lifetimes (esp. protons) decreased x1/2**
- **Emittance growth rates changed: 25 hr → 15 hr**

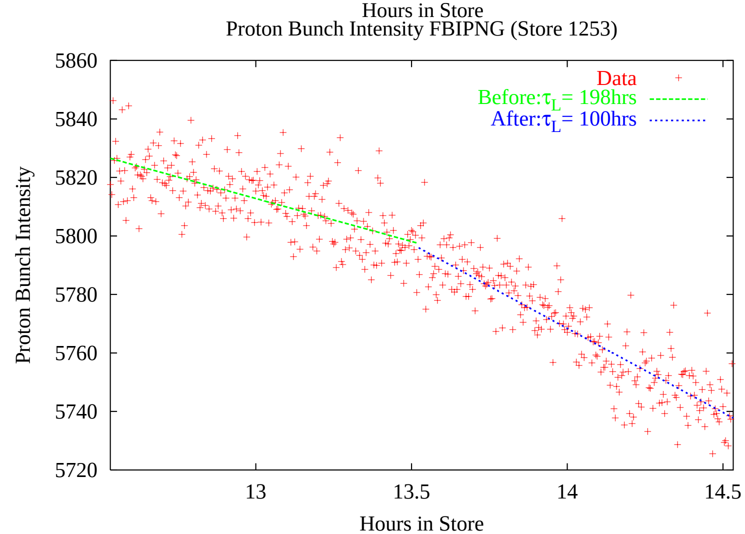




Analysis of Store 1253 (T. Sen)







Calculations:

- Orbit at IP changed by 30 μm; explains ΔL
- Before failure, beam was ~6σ from collimators
- after failure, moved 0.7σ closer

Store 1253 (cont'd):

With simple diffusion model, can estimate change in lifetime expected with changes in effective aperture and emittance growth rate.

The lifetime due to diffusion is given by

$$t_L = \frac{4}{\lambda_1}\frac{a^2}{\beta}\frac{1}{d\varepsilon/dt}$$

where a=aperture @ $\beta(s)$, λ_1 = 1st zero of J_1

and so we would expect

$$\frac{t_L(after)}{t_L(before)} = \left(\frac{5.3}{6}\right)^2\left(\frac{15.3}{24.5}\right) = 0.49$$

The ratio of the observed lifetimes is 100/198 = 0.51

Cause of increase in dε/dt still unknown.

Lattice investigations …

- **Resonance Driving terms due to present magnet configuration (L. Michelotti)**
  - **In 1980's – magnets were "shuffled" with $b_{2,}$ b_4's and $a_{2,}a_4$'s in mind (sextupole and octupole coefficients); lately – only by quench currents**
  - **Procedure minimized driving terms of six resonances, ensuring < 1σ effect of what would be expected from totally random placement of multipoles**
  - **Over 20 years, configuration of magnets in Tevatron has degraded this balancing act, but not severely. Ex: $3\nu_x = 58$ resonance driving term is now about 2.6 times stronger; however, Tevatron would have to approach within 0.002 of this resonance line to have a serious effect**

Turn-by-Turn BPM System

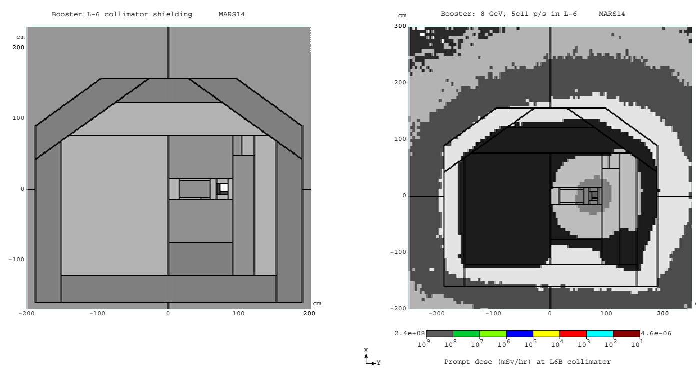
- Current Tevatron System
  - 0.15 mm readback resolution (hardware has 0.01 resolution or better)
  - T-B-T in some BPM’s only; work in progress on ring-wide system

- Applications:
  - Diagnostics of system itself -- bad, noisy BPM’s; resolution measurements
  - Enhanced measurement accuracy via statistical reduction of random noise
  - Linear lattice verification
  - Nonlinear single particle map measurements
  - Effective transverse impedance measurement

Other Support from Beam Physics Dept. …

- **Booster**
  - **Energy deposition**
    - **Beam loss and radiation studies, collimation system design and installation of primary and secondary collimators.**

BOOSTER L-6 MARS MODEL AND DOSE



  - **Injection Lambertson Magnet upgrade**
  - **Space charge calculations / tracking (on hold, but may start again soon)**
  - **Transition crossing simulations**

Other Support from Beam Physics Dept. …

- **Main Injector -- Coalescing calculations; instabilities**
- **Recycler -- Injection, transfers; longitudinal calculations**
- **Run IIb**
  - **Beam-beam**
    - **132 nsec operation**
      - **Crossing angles, tune footprints, etc.**
    - **BB $\Delta\nu$ compensation (electron lens)**
  - **Slip-stacking / barrier bucket**
  - **Electron cooling**
- **Other projects (PD, LC, muons) slowed down (essentially stopped), and efforts redirected toward Run II…**

Other Support from Beam Physics Dept. …

- Computing (1.5 FTE)
  - Administer BD unix cluster for accelerator calculations
  - Administer BD parallel cluster (32 node, 64 CPU) for general accelerator calculations (driven by beam-beam, energy deposition, space charge calculations)
- C0/BTeV -- IR design and beam separation schemes; 0.5 FTE, slowing down
- LHC -- IR designs and tracking studies; phase I and phase II; 1 FTE
- μ/ν -- 3.5 FTE's previously assigned to this effort; now ~1 FTE
- Fermilab/NIU Photoinjector Laboratory (0.5 FTE)
- Finished or slowed projects:
  - NuMI -- redesign of NuMI beam line optics and MI extraction; energy deposition calculations (beam line, MINOS, MI)
  - Proton Driver -- design studies I, and II
  - LC -- had been 2.5 FTE's, recent efforts ~0 FTE
  - VLHC -- led BD portion of 2001 design study last year; presently 0 FTE
  - plus:
    - ICFA meeting, BD/TD seminars,PhD program, …

Further remarks...

- **Work continues on much of above; many other issues – injectors, Recycler, etc.**
- **Some things to do:**
  - **improve impedance model of the Tevatron – Task Force being formed for follow-up**
  - **Continue to improve model of Tevatron lattice, including alignment and other errors – Task Force working on this; new alignment data needed**
  - **further improvements to beam diagnostic analysis using improved Turn-by-Turn BPM system**

Summary of Run II Accelerator Physics Issues

Mike Syphers

Dept. of Energy Review of Accelerator Run II
October 28-31, 2002